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UNITED STATES AIR FORCE

AIR UNIVERSITY

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Wright-Patterson Air Force Base, Ohio

A COMPARISON OF SELECTED SCHEDULING HEURISTICS FOR A TAC F-4E MAINTENANCE ORGANIZATION

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Scheduling of activities in simple and complex environments has been a subject of active research for many years. The USAF has actively supported such research in its continuing efforts to determine the impact of scheduling effectiveness on mission capability. The recent validation and availability of the Logistics Composite Model (L-COM) made it possible to test selected scheduling heuristics in the dynamic maintenance environment of a TAC F-4E squadron. Five heuristics were formulated, inserted into the model, and allowed to operate during simulation. Results of the simulation indicated that the selected heuristics did impact mission capability, that rank ordering occurred between them, and that there was a statistically significant difference between the worst and the best heuristic (88.15% to 91.57% sortie effectiveness).

SLSR 23-76B

A COMPARISON OF SELECTED SCHEDULING HEURISTICS FOR A TAC F-4E MAINTENANCE ORGANIZATION

A Thesis

Presented to the Faculty of the School of Systems and Logistics

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Air University

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Logistics Management

By

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Chapter 1

STATEMENT OF THE PROBLEM

The setting in aircraft maintenance operations is conducive to the application of sound scheduling rules; it is a dynamic environment consisting of multiple independent jobs requiring accomplishment while subjected to multiple constraints--the most unpredictable of these being unscheduled maintenance requirements. Jobs occur in a random fashion necessitating the dispatch of finite resources by some priority procedure.

There is a continuing concern in the United States Air Force about scheduling effectiveness and its impact on mission capabilities (3:1). Although considerable research has been done in the area of scheduling, no specific dispatching rules have been developed to date which have proven effective for directing the operations of a typical F-4E aircraft maintenance organization. In particular, USAF directives do not prescribe specific scheduling rules for unscheduled maintenance (22). Many heuristics are used to cope with the dynamic environment which exists in the maintenance control portion of the maintenance complex, but these *rules of thumb* (heuristics) achieve varying degrees of effectiveness based on the skill of the controllers.

Succinctly stated, the problem is that specific scheduling rules for unscheduled maintenance which consistently and effectively achieve desired performance objectives for a Tactical Air Command (TAC) F-4E maintenance organization, have not been developed.

Definition of Terms

a. Scheduling Heuristics are rules of thumb which "are analogous to priority rules and dispatching rules but in general lack the analytical support to make them acceptable in the scientific world [2:7]."

b. Scheduling is the assignment of order or precedence, time, and resources to a job.

c. Dispatching is synonymous with scheduling.

d. Attributes are elements of a model which have numerical values subject to periodic changes.

e. Entities are attributes that have been grouped and named according to type. Entities may be either permanent or temporary.

f. A set is a group of entities.

g. Events are changes which involve numerical operations on attributes.

Justification

United States Air Force and Tactical Air Command interest in the development of scheduling rules for application by base level organizations is evidenced by requirements set forth in A Study of the Automation of the

Logistics System at Base Level (STALOG) (24). As early as 1968 "The Vice Chief of Staff . . . directed that a major study be undertaken to determine the best method for automation of logistics at base level [24:I-1]." The study was completed in 1970, and in April 1971 guidance was given to a select group to begin development and implementation of proposed concepts of operation. Scheduling rules for inclusion in the maintenance portion of the system have yet to be developed.

> These scheduling rules must be developed for utilization by the STALOG computer in order to achieve a dynamic scheduling capability within STALOG and thereby claim the full range of benefits predicted under the STALOG concept of operations [23:XXI-8].

Development responsibility for these rules has been directed towards the Air Force Logistics Policy and Procedures Division (AF/LGYP) with additional representation suggested from the Air Force Institute of Technology (AFIT), Air Force Data Systems Design Center (AFDSDC), and the RAND Corporation (23:XXI-9).

The Air Force has maintained a high interest in developing priority dispatching rules as evidenced by contracts to the RAND Corporation for research in this area (4; 12; 13). Each report has added to the growing body of knowledge about the effect of different scheduling rules, yet the results of the research suggests a need to develop a rule or combination of rules that will operate in a dynamic complex assembly environment. Miller, Ginsberg and Maxwell highlighted this need by stating:

> The Air Force's study of the Automation of the Logistics System at Base Level (STALOG), the recent Maintenance Management Information and Control System (MMICS) field test at K. I. Sawyer AFB, Project Early Bird [an ongoing field test at Ogden Air Materiel Area (AFLC)], as well as some recent component repair scheduling research conducted by members of the AFLC in support of the Advanced Logistics System--all highlight the need for more basic understanding of job scheduling for complex products [13:iii].

In the generic terminology of job shop scheduling, a *typical* Tactical Air Command F-4E Maintenance Organization may be viewed as a dynamic complex assembly shop whose output is highly dependent upon the effectiveness of scheduling. A review of the literature indicates that limited progress has been made in developing and testing scheduling rules that could assist decision makers (schedulers/maintenance controllers) in consistently achieving the maximum number of operationally ready aircraft (to support a maximum number of sorties) with a finite number of resources.

Perhaps the most direct way of emphasizing the capability of scheduling rules to increase operational ready rates is to cite an example. As gleaned from Boyett, the situation may be considered where two aircraft become inoperative at 0100 because of different malfunctions. Each malfunction takes one manhour for correction and may be cleared by one man in one hour or two men in one-half hour. If two maintenance men are available between 0100 and 0200 a decision must be made to allocate their work time; e.g., assign one man to each aircraft or assign both men to first one aircraft and then the other. In the first

case, both aircraft are repaired by 0200, the maintenance men are used 100 percent of the time, and the aircraft in-commission rate is zero percent for the period 0100 - 0200. In the second case, the maintenance men are both used 100 percent of the time but the aircraft in-commission rate is significantly different; i.e., one aircraft is placed back in commission at the end of the first half hour and results in an in-commission rate of 25 percent (one half hour divided by two hours times 100) (3:2-4).

Obviously, the second scheduling technique increased the in-commission rate and, as opposed to the "almost universal belief that one cannot increase response capability without either increasing resource quantities or increasing utilization of existing resources . . . [3:2]," it did so without changing anything but the scheduling method. This simple example should not be taken too lightly, for the positive impact, although not necessarily as dramatic, can also be shown in complex real world settings.

Boyett emphasizes that a need exists to test, using computer simulation, a selected set of heuristics to determine those that would "consistently produce good schedules relative to the measure of scheduling performance [3:18]." He further recommends that:

> . . . the following heuristics be included in the set of heuristics tested.
>
> a. First arrive first served; all jobs are assigned a priority equal to the arrival time of the aircraft. Resources are dispatched to the job with the lowest [numerical] priority.

b. First come first served; all jobs are assigned a priority equal to the time at which its last predecessor's job is completed. Resources are dispatched to the job with the lowest priority.

c. Shortest job process time; all jobs are assigned a priority equal to the expected process time. Resources are dispatched to the job with the lowest priority.

d. Shortest assembly path; all jobs are assigned a priority equal to the expected minimum flow time for a parent assembly. Resources are dispatched to the job with the lowest priority [3:19].

The need for further research apparently exists, and the vehicle that is available to simulate the actual maintenance environment is the Logistics Composite Model (L-COM). This computer model was used to develop manpower requirements for a TAC F-4E maintenance organization. "L-COM was selected because of its flexibility in that it can portray various maintenance environments through predetermined flying schedules [21:1]." Ability to duplicate the aircraft maintenance environment was validated. The TAC L-COM study also states, "the value of this system by users other than manpower, while difficult to determine at this time, is nonetheless evident [21:2]."

It appears that with the development requirements of STALOG and similar management systems, further research in identifying and testing selected heuristics, using the dynamic simulation capability of L-COM, is warranted.

Delimitations

The delimitations of the research are as follows:

1. The computation of OR rate in the L-COM model (SIMSCRIPT 1.5) was found to be inappropriate; therefore, following the precedent of TAC in using sortie effectiveness as a key performance criterion, this research used sortie effectiveness (ratio of sorties accomplished to sorties requested expressed as a percent) as the single measure of effectiveness of the selected scheduling heuristics.

2. The L-COM was the sole source simulation model to be employed. The limitations it has are an inherent part of the results of this research.

3. The scheduling rules tested were limited by the job characteristics defined in L-COM (sets, entities, attributes).

4. The number and length of simulation runs for each heuristic was limited by computer availability.

5. Actual field validation of the selected heuristic(s) was not accomplished.

Objective

The objective of this research was to identify a scheduling rule or combination of rules which consistently maximizes sortie effectiveness for a TAC F-4E squadron.

Research Hypothesis

There is a difference in the impact on scheduling effectiveness between alternative selected heuristics.

Chapter 2

BACKGROUND

Scheduling of activities in simple and complex environments has been a subject of active research for many years. Numerous theories have been developed during the quest for a *best* method of scheduling in all situations. In-depth research was initiated in 1964 by the United States Air Force with a contract to RAND Corporation to explore the impact of applying priority assignment rules to a maintenance environment (4). Since that time, studies have centered around developing effective dispatching procedures for independent job shop operations. The thrust of the research has been directed towards a commercial application including the publishing of text books (5; 16) on scheduling theory as an emerging management discipline.

A multiplicity of dispatching problems and associated heuristics have been considered and evaluated during the period of study devoted to scheduling theory. Each contribution of research to the growing body of knowledge led to suggestions for further investigation and replication.

One of the first attempts to comprehensively organize the relatively divergent work that had been done on scheduling prior to 1966 was accomplished by Conway,

Maxwell and Miller in 1967 (5:v). Their text, Theory of Scheduling, appears to serve as a fundamental reference for the field of scheduling theory and as such incorporated extensive results of research work from a cross-section of significant contributors; e.g., RAND Corporation, Western Electric Company, The Office of Naval Research, The National Science Foundation, General Electric Company, Cornell University, Management Science Group, and numerous individual contributors. Within that text may be found a comprehensive assessment of the various job shop, flow shop and general N/M (N--jobs; M--machines) job shop problems that comprised the field of interest to that date and which still continue to be subjects of investigation. In general, it may be observed that significant advances in resolving static simple job shop problems was reported. However, their recognition of the potential of heuristic approaches to job shop scheduling is most relevant to the proposed research. Heuristics, as pointed out by Boyett "are analogous to priority rules and dispatching rules but in general lack the analytical support to make them acceptable in the scientific world [2:7]."

Research in the area of scheduling continued with the static job shop being the primary focus. Spinner (18) in 1968 reviewed the research to date and found that studies on sequencing theory, inclusive of scheduling--dispatching--and sequencing, assumed that all factors in

the job process were known. With this restriction *a priori* schedules can adequately predict the outcome of a particular experiment. Little research had been published on attempts to develop new or improved models that considered methods for dealing with unknown occurrences, or probabilistic events, in a job process (18:370). Spinner emphasized that the shop:

> . . . where technological imperatives 'do not' completely dictate the sequence of operations for each job lot in production, represents the area where sequencing theory could be of most benefit and is presently of least benefit because of a lack of constructive work in this area. . . . That is, the models proposed to date attempt to predict the progress of each job in detail based on 'a priori' technological sequences for each job in production; thereby the real problem of industrial sequencing goes lacking for a solution [18:322].

Simulation techniques were beginning to emerge during this period but few applications had been made to the area of sequencing problems. Sequencing theory as viewed by Spinner is a combination of sequencing (a set of directions governing the route of a job during its entire process), queueing or dispatching (the assignment of order or precedence to the job) and scheduling (the assignment of time and resources to the job) (18:320). The application of heuristic priority rules in the research is analogous to Spinner's definition of queueing or dispatching. Although these terms are used interchangeably (scheduling, dispatching) the discussion is primarily

directed towards the dispatching function of sequencing theory.

In 1970, Day and Hottenstein pointed out that

> . . . the majority of research articles published on job shops appears to be concerned with the effects of scheduling and sequencing (dispatching) on various measures of shop performance criteria [6:11].

They reported that those articles usually dealt with the effects of scheduling in terms of some combination of topics described in three classifications as follows:

1. Number of component parts comprising a job
   a. Single-component jobs
   b. Multi-component jobs which require assembly and/or subassembly operations
2. Production factors possessed by the shop
   a. Machines
   b. Labor and machines
3. Jobs available for processing
   a. N jobs to be scheduled, or sequenced, where N is finite. This is often referred to as the static scheduling or sequencing problem . . .
   b. An undetermined (literally infinite) number of jobs arrive continuously, but randomly, at the shop for service. This is often referred to as the dynamic sequencing problem . . . [6:11].

Of these classifications, research was reportedly scant on multi-component, labor and machines, and dynamic sequencing composite problems. Rather, the preponderance of work was still directed towards the highly deterministic environments; i.e., classifications 1a, 2a, and 3a above.

In addition to the classifications above, Day and Hottenstein developed a classification or taxonomy of sequencing problems, Figure 1, which was used as an instrument to facilitate the discussion of research results.

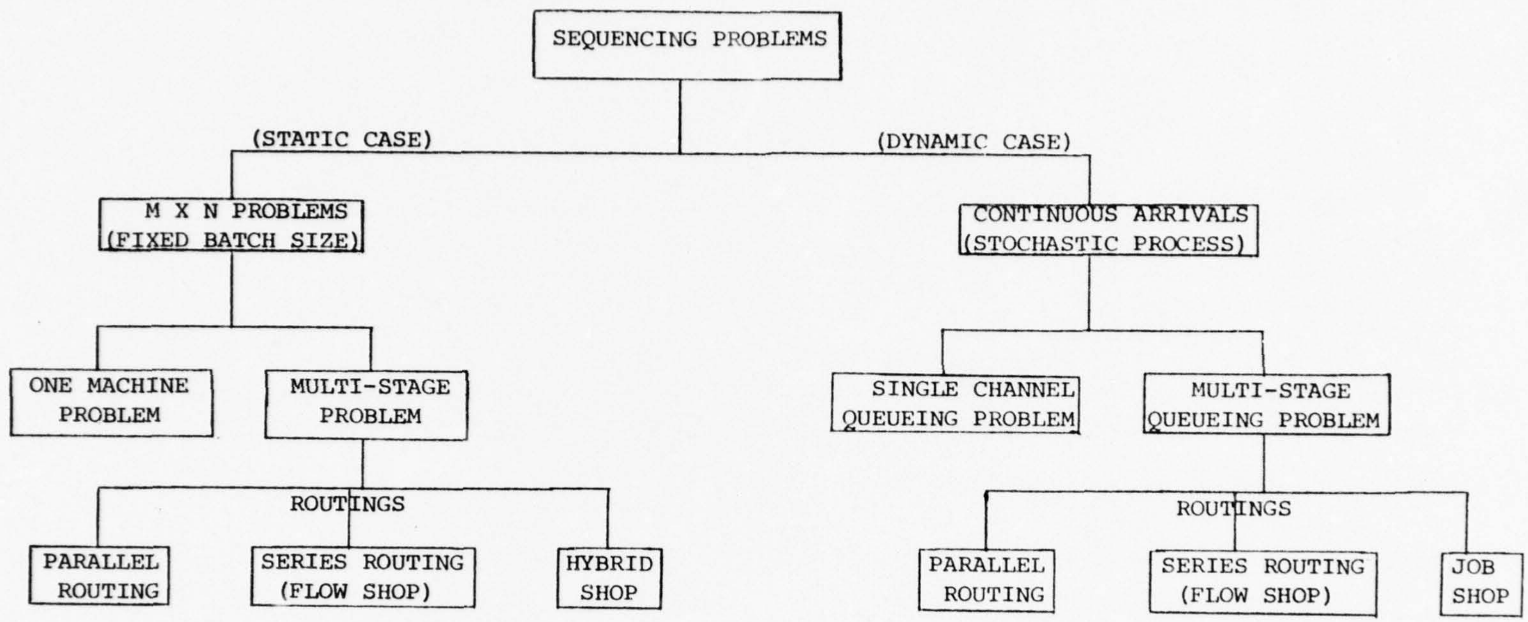

Figure 1

A Classification of Sequencing Problems (6:12)

Of particular interest was the review of dynamic sequencing problems and the identification of:

1. typical assumptions used in dynamic job shop studies;

2. common shop load parameters used in simulation studies of dynamic job shops;

3. operational characteristics of the simulation system;

4. the Monte Carlo simulation as the principal tool of analysis;

5. queue discipline; and

6. types of priority rules: lateness rules, arrival order rules, rules based on some property of the job and random rules.

With regard to priority rules it was observed that "no analytical formulation has been made which assures optimality [6:20]" and that a "generalized statement of the relative effectiveness of priority rules in relation to a given criterion is difficult, if not impossible, to make [6:21]." Further,

> . . . the simulation model may be improved by the inclusion of a set of heuristic rules to bolster the dispatching rules already in use. Gere has successfully applied heuristic rules to the static M X N stochastic sequencing problem and it appears that the inclusion of heuristics in the dynamic job shop model will also yield improved results [6:26].

While the thrust prior to the Seventies was centered around the *static* job shop environment, recent

emphasis has been on treating the operation as a dynamic unit requiring investigation of the effect of priority dispatching rules. The availability of computer systems to aid the scheduling process and, more importantly, their ability to provide accurate simulation of real life environments, has led to greater research into dispatching rules for the dynamic shop operation.

One significant development in 1970 was the formal recognition of a need to develop a responsive and precise method for determining maintenance manpower requirements. From this concept came the development of the Logistics Composite Model (L-COM) that had the capability to simulate a dynamic job shop environment. Although its original intent was to determine manpower requirements, its subsequent field test and validation (in 1973 at a Tactical Air Command F-4E maintenance organization) provides an accurate base point to evaluate scheduling rules (21:1).

Perhaps in consonance with the emergent interest in applying heuristics to dynamic job shops, Boyett completed a doctoral dissertation in 1972 titled "Effectiveness of Heuristics in a Dynamic Complex Assembly Shop." The study employed a simulation technique in analyzing the "effectiveness of a limited number of heuristics in sequencing operations of jobs in a dynamic complex assembly shop [2:iii]." Fourteen heuristics (and one tie-breaking rule)

were employed. The simulation results led to the major conclusions that

> . . . an a priori conclusion cannot be made that a simple variation of shortest processing time heuristics will produce significantly lower flow time statistics. Analysis of data indicates that a good heuristic must effectively operate on three factors; awaiting predecessor time, awaiting work time and awaiting job completion time [2:iv].

Further work on scheduling by Elvers in 1973 focused on analyzing

> . . . the results of applying various decision rules to a job shop scheduling situation where (1) the scheduled machine times are not deterministic and (2) the due dates are determined by different decision rules [8:62].

The study did employ a complete simulation technique; however, the research environment was limited to only eight single process machines. Further, only tardiness was used as the basic criterion for evaluation of scheduling rules. For three categories of tardiness rules,three scheduling rules were determined to be the best predictors: minimum remaining processing time (MINRPT), minimum processing time per operation (MIPTPO) and minimum imminent operation time (MINIMM) (8:68). The results, however, must be considered restricted in application because of the limitation of his model and the model's lack of further validation.

Another contribution to the field of scheduling theory was made in 1974 by Miller, Ginsberg and Maxwell. Their work involved the use of computer simulation to experimentally investigate a simple assembly shop. Their

shop dealt with random arrivals of products; i.e., unscheduled aircraft maintenance, "composed of a random number of jobs, with each job requiring processing by a single specific type of machine (skill category) [13:v]." In that regard, their shop resembled a simplified version of the complex shop investigated by Boyett and Maxwell and was thus construed to be "a step backwards [13:2]." Of particular interest however, was the fact that their application was directed towards unscheduled aircraft maintenance. Their work tested a number of scheduling rules and, a best rule was identified. Their best rule, of sixteen tested, was the smallest total work content of unstarted jobs (TWC-US). "That is, give highest priority to the set of waiting jobs whose product has the least sum of processing times [13:v]." Conversely, for their application, two popular and previously identified best rules (first come first serve and shortest processing time) were found undesirable. There were however, significant limitations to their work. As recognized by the authors their model was grossly simplified, used known process times, and perhaps led them to the suggestion that

> The best a scheduler or system designer can do is attempt to synthesize a solution out of methods and qualitative notions that have emerged from studies such as this one [13:24].

Ambre, on the other hand, conducted a study in the aircraft maintenance environment, and found the first in first out (FIFO) rule to be the most desired. Primary

intent in this case was to test heuristics, using a Weapons System Availability model (WSA), and determine those rules best suited for automation. He concluded that "since the FIFO rule is the most efficient, it would over the long run maximize efficiency by minimizing system non-availability . . . [1:48]." However, he strongly recommended continued action to evaluate and test scheduling rules using simulation models (1:48).

Further work in the scheduling area continued in 1975. Of particular note to the proposed study are articles by New (15) and by Hershauer and Ebert (11).

New's article indicated that "Many computerized production scheduling systems have been implemented in order to make use of job dispatching rules for sequencing work on facilities [15:35]" but that little, if any effort has been expended to develop manual systems. He attributes the lack of effort to the general belief that the employment of good dispatching rules without using a computer is impossible. To refute this notion, New cites supporting experimental results and then describes a manual sequencing system that can be used in conjunction with scheduling heuristics.

Hershauer and Ebert, on the other hand, suggest the employment of a validated computer model as a first step in developing an approach which focuses on "a method for finding a sequencing rule that performs well in any specific job shop situation [11:833];" as opposed to a single

best rule. The ability of simulation models to accurately duplicate real life environments has long been suspect and reflects on the acceptance and validity of research results. Succinctly stated:

> If the simulation model is in complete agreement with the actual shop parameters, then the simulated and actual shop activity would be identical; however, due to the many assumptions built into the simulation model this seldom occurs. Hence one is faced with the question of validity, to the degree to which the assumptions made in the simulation represent the situation in the real shop [6:28].

It is then critical to insure that the simulation model employed for testing the various heuristics be able to truly represent the environment under investigation. The Logistics Composite model was one of several models evaluated by the United States Air Force, beginning in 1970, to be used as a predictor of maintenance manpower requirements. "L-COM was selected because of its flexibility in that it can portray various maintenance environments through predetermined flying schedules and resources [21:1]." To insure that the L-COM model could simulate the actual conditions present in an aircraft maintenance environment, a field test was initiated using a TAC F-4E wing, as a base line, for a comparison of model predictions and actual conditions.

The model consists of a preprocessor (accepts network input data), main simulation program (manipulates input data and contains basic decision logic) and post processor (displays output data). The task structure of the wing is

input into the model in the form of networks describing every task required to accomplish a component repair. The user structures this network such that it describes the environment, with applicable constraints, which exists to support a desired flying program or scenario.

The simulation program processes the structural image of the wing and proceeds to operate on specific parameters necessary to duplicate occurrences that are actually present in a real maintenance environment. Artificial "failure clocks," driven by a random number generator, simulate failure of aircraft components. The flying schedule is considered, and a predetermined priority system is employed to provide resources and material capable of repairing the inoperative part. The internal logic of the main program simulates the dynamic environment of the maintenance operation and subsequently creates operationally ready aircraft. The post-processor outputs the data in a form capable of being analyzed by the user.

The decision logic in the model makes three assumptions concerning task accomplishment. First, the basic priority system assumed by the model is a modification of the first come first served rule. The user establishes initial priority grouping by task type in the input data. Subsequent priorities in each major grouping are assigned by resources available at the time of failure. Jobs for which resources are available are placed into work, but those

that cannot be accommodated are placed in a backorder status queue, at the bottom or last position in the list. This process is basic to the logical flow of events in the simulation model and all other events interact with it. Second, the model assumes that the initial task structure of the Wing will not be changed during simulation runs. Third, the assumption that a finite number of resources are available at any given time, indicates that real world constraints of men, money and materials are accounted for.

In general, the preponderance of research accomplished to date has yielded unsatisfactory solutions to the problems of dynamic complex assembly shops. Specific scheduling rules or combinations of rules necessary to produce effective results within the constraints of the dynamic tactical F-4E aircraft maintenance environment, have not materialized. It should be noted that because of the size, complexity and probabilistic nature of these assembly shop problems, an optimal solution using mathematical programming is not possible today. Simulation, however, is capable of addressing this complex environment.

The L-COM, with its demonstrated ability to replicate the reality of the maintenance environment,[1] is now available to simulate the aforementioned conditions and allow further testing of scheduling rules.

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[1]Documents with a detailed explanation of the structure and operation of the Logistics Composite model and its subsequent validation are available (9; 19; 20; 21).

Chapter 3

EXPERIMENTAL DESIGN

Input Data

The primary data input for simulation runs used in this research was essentially the same TAC F-4E data package and flying scenario which was used in the successful validation of the L-COM. The F-4E data package (structural image of the wing) and the flying scenario are maintained on an exogenous (external) tape and were used repetitively from run to run.

The exogenous tape, which was obtained from TAC, contains two major elements of the simulation; the F-4E data package or support environment and the flying scenario (both may be modified independently). The support environment is comprised of selected resources (e.g., personnel, supplies, test equipment, etc.) and corresponding time expenditures and activities (e.g., bench check, repair, failure, etc.). This environment is described for the model as a network of tasks as opposed to the flying scenario which provides detailed flying requirements in terms of number of missions, takeoff times, mission size and length, etc.

The task networks are fundamental to the realistic operation of the model. They are composed of tasks which

may be defined as requirements for men, parts and equipment that have a defined relationship with other tasks, in terms of either successor, parallel or series tasks. Because of their key role in the model a simple task network is illustrated in Figure 2 followed by an explanation, which was extracted from the L-COM user's guide.

Each task within the network is explicitly defined and recorded in a task table. It is to these tasks that priorities germane to the heuristics to be tested are assigned and which were the object of manipulations addressed later in the study.

The input data, as just described, were not physically modified during the simulation runs; i.e., the exogenous tape has been retained intact. However, the input data was modified to allow practical duplication of the resource constraints used by TAC in their final report. In brief, the same manpower and equipment authorizations were retained (Tables 1 and 2 respectively; see Appendix[1]); and, the same task networks and flying scenario were retained but the spare parts authorizations (Table 3) were modified appreciably. The modification of parts authorization insured: (1) the suppression of the performance criterion (sortie effectiveness) to a low enough level (approximately eighty-eight percent) to provide ample room

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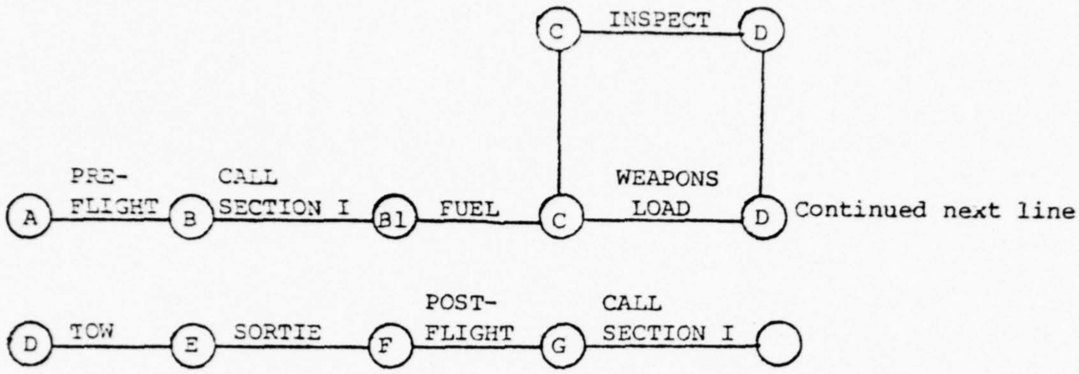
[1]All of the tables referenced within the text of this thesis appear in the appendix.



In the example, the sortie is the series successor to the tow task. The inspect task is the series successor to the fuel task, the weapons load is a parallel task to the inspect task. The description of this network of tasks is flexible in that it can be described by the user to any degree of simplicity of complexity desired. An additional feature permits the network to be designed in sections, thereby reducing the complexity and size of the network input data. A separate section which is utilized can thus be defined only once and called from several locations within the network. As in the example, this might be a maintenance action or actions possible in both pre- and post-sortie periods of time. The size of these sections is not limited.

During the simulation, task network processing is started by defining an entry point to the network and mission type that will trigger this initial entry. Each entry generates an explicit network identifier which has associated with it an aircraft or part resource that is controlled by the network until its processing is completed and the associated part is released. The network identification is established to permit a series of tasks to generate new series of tasks involving network. This is exemplified by repair of an aircraft generating a reparable to the shop, the repair of the reparable generating repair of a sub-assembly, etc. [19:4-5].

Figure 2

Simplified Task Network

for variation; and (2) an increase in the overall sensitivity of the model to changes in the scheduling rules. In addition, the length of simulation runs was changed to eighty days and the reports cycle was changed to ten days. The eighty-day period provided accommodation of the computer usage constraints addressed in the delimitation section while the ten-day report cycle generated eight reports on sortie effectiveness which were used for trend analysis. The eighty-day period generated an average of 160,000 jobs and was held constant for each different heuristic and four random seeds used in the study. Of particular significance was the identification of the task attributes which would be used in the formulation and employment of the scheduling rules to be tested. They are briefly described in the following paragraph.

The set of tasks awaiting work is identified in L-COM as a general purpose ranked set. It contains tasks which are ranked on various attributes; e.g., the aircraft mission priority, task mean process time, time in back order, etc. Specifically, mean job process time, priority of the task and arrival time of the task were identified to suit the purposes of this research. How these attributes were employed is explained in the following section.

Manipulation of the Model

The L-COM main simulation model is programmed in SIMSCRIPT I.5 (computer language). In order to change the

scheduling philosophy designed into the model, it was necessary to change the combination of priority attributes used to sequence tasks in the awaiting work set. The priority system for unscheduled maintenance is divided into three major groups with variable dimensions. The initial group priority for a particular type of task was specified by TAC during development of the input task networks. Each task type was rated as to its relative importance in the scheme of accomplishing aircraft or component repair and was given a group priority of either one, two, or three. On one hand, the "on aircraft" test of a failed electronic part would be considered a short term "quick fix" action that should be accomplished as soon as resources are available and would be given a group priority of one. While on the other hand, the in-shop disassembly and subsequent repair of this same electronic component, would require much more time than the test task, and would not lend itself to being capable of returning the aircraft to an operationally ready status in minimum time. It would therefore be given a group priority assignment of three. Each task is identified and maintains its group priority assignment during the operational run. The priorities assigned to the tasks are by urgency of need. Once a task is assigned a certain group priority it must compete for a relative ranking priority within that group. Many factors interact to establish this ranking and it is this

specific ranking which was manipulated using the experimental heuristics. There are four situations that can exist at the time a task is generated:

1. resources are immediately available when the task is required,

2. resources are not available but are being utilized by a task of lower priority,

3. resources are not available but may be released in a short period of time, and

4. resources are not available and require a substantial wait.

In the first case, since resources are available, the task is put into work. The second situation addresses the preemption capability of tasks based on priority and ranking. If the resources required for the new task are being utilized by a task of lower priority, then the new task preempts the resources and is entered into work. The third situation assumes that both tasks competing for the same resources have equal priority and ranking, and that the time to complete the existing task is sufficiently short to justify waiting for the resources. The fourth situation acknowledges the unavailability of the resources and enters the task into a backorder awaiting work set.

The priority groups, as previously mentioned, have adjustable dimensions. However, these were not changed and the normal default modes set at 0 to 10 for Group 1,

11 to 20 for Group 2 and 21 to 30 for Group 3 were used. The scheduling philosophy utilized by L-COM for the validation and field test was a <u>Modified First Come First Served</u> rule. The priority was established by selecting the lowest number (highest ranking) from the group specified by the given task priority. For example, if a given task type was assigned a priority group 1 in the task network, when it became a candidate for processing it would be assigned a priority ranking (hereafter referred to as TPRI) of 10 for this particular task. The program then identifies from the task table the resources required to process this task. After these requirements have been determined a resource table (maintains current balance of all resources on hand) is checked. If the necessary resources are available the job is placed into work. If the proper type and quantity of resources are not available further screening is required. A check of the resource table is made to determine if substitute items are available. If not, tasks currently using the needed resources are checked to determine when they will be completed. If the completion time is within the specified waiting time criteria for the incoming tasks, the latter is set aside and the former is expedited. Resources, however, are not reserved for the incoming tasks; for example, another incoming task of higher priority could receive the needed resources. If the incoming task has a higher priority than the task being

processed, it can preempt the latter and obtain the resources.

Tasks are placed in an awaiting work set when the above mentioned procedures do not allow it to obtain resources. When a processing task is completed, resources are released and five jobs with the highest priority, in the awaiting work set are removed and ranked according to this priority. These tasks are now treated the same as new tasks entering the system and the search procedure is repeated.

It is at the point of setting the priority for the incoming task, and subsequently its ranking in the awaiting work set, that the experimental heuristics are applied. Using an expanded equation, five heuristics were applied using the available attributes, processing time, lapse waiting time and TPRI. For example, if the shortest processing time parameter is to be used for primary ranking and TPRI is used as a first order tie breaker, the priority ranking equation will resemble the following:

$$\text{RANKING PRIORITY (PRI)} = (10^4) * \text{MPT} + \text{TPRI}$$

where MPT = 4 digit number--mean processing time, and

TPRI = 2 digit number--default mode priority.

The rules are discussed in narrative form below, with a formal definition of the applicable mathematical and SIMSCRIPT I.5 coding presented in Tables 4, 5, and 6.

Modified First Come First Served (MFCFS). The task awaiting work set is ordered at the time a task was refused resources and began awaiting work. The task is initially given the priority TPRI when it arrives as a candidate for work, and maintains this priority as the aforementioned screening process is accomplished. The task then enters the awaiting work set and its priority is increased by a time factor as it waits in the set. This procedure prevents a task from remaining in the set permanently while higher incoming priority tasks are processed. For example, an arriving task that is specified by the task network as a group priority 2 would be given a TPRI of 20 and would continually be preempted by all tasks that entered the group priority 1 and were given a TPRI of 10. Ties (numerically) are possible with this procedure as the TPRI is an integer value and the actual TPRI will not change until the decrement factor achieves the next integer value. For this reason, as the tasks are removed from the set as candidates for processing, shortest processing time is used as a tie breaker and the highest priority task, with resources available is placed into work. A task can enter the awaiting work set only if its individual predecessor set is empty. The MFCFS departs from the traditional concept of a first come first served (FCFS) rule where the awaiting work set is totally ordered by the time a task began awaiting work. The MFCFS heuristic tested, follows

a FCFS philosophy within groups which were defined based on task significance. The priority equation is given as:

$$\text{RANKING PRIORITY (PRI)} = (10^4) * \text{TPRI} + \text{MPT}$$

The lowest numerical value, or first in set, is put into work first.

<u>Shortest Mean Processing Time (SMPT)</u>. The tasks competing for resources, as candidates for processing, are given an initial priority based on mean task processing time. This priority is used in the screening process and subsequently to order the task in the awaiting work set. First order ties are broken by using the attribute TPRI. This action has the effect of considering all tasks as equally important and working those with the shortest processing time. The only time the importance of the job is considered is when ties exist, and then the job specified as having a higher group priority in the network, will be worked first. The task duration is ". . . selected as a random draw from a probability distribution of the specified type, with a mean and variance as indicated [9:100]." The priority equation is given as:

$$\text{RANKING PRIORITY (PRI)} = (10^4) * \text{MPT} + \text{TPRI}$$

The lowest numerical value, or first in set, is put into work first.

<u>Longest Mean Processing Time (LMPT)</u>. This heuristic is the inverse of SMPT. The first in set (lowest numerical value) philosophy of selecting a task for work, in L-COM, necessitated computing the inverse of the processing time to insure that the longest processing time would be first in set. Tasks are ordered by processing time with first order ties being broken by TPRI. Processing time is determined as specified in the SMPT section. The priority equation is:

$$\text{RANKING PRIORITY (PRI)} = (10^4) * \frac{1}{\text{MPT}} + \text{TPRI}$$

The lowest numerical value, or first in set, is put into work first.

<u>First Come First Serve (FCFS)</u>. The tasks entering the system, and competing for resources as candidates for processing, are given a priority equal to their arrival time in days elapsed since the start of the simulation run. The awaiting work set is totally ordered by the arrival time of a task to the system. The attribute used to assign this priority was "time"; a built-in system attribute of SIMSCRIPT I.5 which is given in decimal days. Time is set to zero at the beginning of the simulation run. A task can enter the awaiting work set only if its individual predecessor set is empty. Task priorities are increased in the awaiting work set based on the length of time the task is in the set. The priority equation is:

RANKING PRIORITY (PRI) = (10^4) * Time

The lowest numerical value, or first in set, is put into work first.

Estimated Time of Completion (ETOC). This heuristic combines the features of first come first served (FCFS) with those of shortest mean processing time. Tasks competing for resources and subsequently entered into the awaiting work set are ordered according to the time they entered the system plus their mean processing time. This combination of attributes results in a computation of the estimated time of completion for the task. The awaiting work set is totally ordered by this estimated time of completion with TPRI used to break first order ties. The use of TPRI to break ties assumes, as has been the case in the other four heuristics used, that tasks identified by the user as having a higher relative importance than other tasks, will be worked first. The priority equation is:

RANKING PRIORITY (PRI) = (10^4) * (Time of Arrival + MPT) + TPRI

The lowest numerical value, or first in set, is put into work first.

The estimated time of completion rule was not designed to approximate due date rules. Establishment of due dates for task completion is not developed in the L-COM

simulation model. Introduction of an artificial method of establishing due dates was not possible in that the simulation does not account for all tasks that are required to return the parent job to a serviceable status prior to the failure of each subsequent task. This same limitation prevents the testing of a First Arrival First Served rule (arrival time of parent job) and also the Fewest Remaining Tasks to Go rule. In each case identification of the tasks being processed or awaiting work are not readily identifiable to the status of tasks remaining for the total parent job. The heuristics tested, utilized attributes that were readily available at the point where task priority was set and did not depend on the dynamics of the simulated environment.

Simulation Runs

The five heuristics tested were entered into the main model section of L-COM. Each rule was structured to insure compatibility with existing program parameters and SIMSCRIPT I.5 coding requirements. The coding statements used and the source line of insertion in the program are identified in Table 6 for each heuristic.

A pilot study was initiated using sample input data to evaluate the operation of the L-COM model. Several sample runs were made, using the existing random seed[1] of

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[1]A random number seed which is the initializing value for a sequence of random numbers (17:176).

85, to determine the model's ability to replicate performance data over identical runs. The sample runs did in fact produce identical results when operating with identical input data. Initial runs were made over a forty-day period to conserve computer run time.

Results of the run were obtained through normal use of the model's post-processor functions. The performance measure used to analyze the affect of each heuristic, sortie effectiveness (number of sorties accomplished versus number required), was included as an integral part of the formatted output.

The exogenous data that was obtained from the TAC validation project was then entered into the simulation. Three runs were made with all resources (parts, men, equipment) unconstrained to insure that the performance measure was produced in an acceptable range, between 90 percent and 100 percent. Results of the TAC validation study reported a sortie effectiveness rate of approximately 90 percent given various resource constraints. An unconstrained run, then, was expected to produce a sortie rate between this limit and 100 percent. The sortie rate obtained was 96 percent and the results of each run were identical.

The pilot study was concluded and a structure was developed to accomplish the final runs (using a 10-day report cycle--80-day flying period--and 18 assigned

aircraft) to test the five heuristics. Each heuristic was run using the random seed 85 used in the validation study. Four subsequent random seeds that were known to be acceptable (7) were used to test each of the five heuristics. A total of twenty simulation runs were made with each heuristic being used for random seeds 85, 13, 15, and 93.

Analysis of the results obtained for each heuristic is presented in Chapter 4.

Chapter 4

ANALYSIS AND RESULTS OF SIMULATION

The primary data extracted from the simulation runs was the performance criterion, sortie effectiveness, as printed out in the post-processor generated performance summary. As a result of the eighty-day period/ten-day report cycle that was selected, eight ten-day performance summaries were generated per run. Those summaries listed the sorties requested, sorties accomplished and sortie effectiveness (ratio of sorties accomplished to sorties requested expressed as a percent) for each ten-day period. Table 7 through Table 11 provide a listing of that data for each rule and each seed used in the experiment.

The data referenced above was then aggregated for the period from zero to eighty days and twenty to eighty days by summing the sorties requested and sorties accomplished for the appropriate periods. The twenty to eighty-day data was used to evaluate the heuristic scheduling rules, with the zero to eighty-day data being included only for completeness in data reporting. The exclusion of the zero to twenty-day data was necessary to allow for the attainment of steady state conditions (7; 9:61; 17:180-181) prior to evaluating the effect of the scheduling heuristics on sortie effectiveness. The aggregate data for each

heuristic and seed is displayed in Tables 12 and 13. In addition, the number of tasks started, tasks completed, percent accomplished and number of preemptions for each run are shown in Tables 14 and 15.

Although percentage of task accomplishment and preemption were not the focus of this study, it was observed that appreciable variation in the number of preemptions did occur from rule to rule, although the percentage of tasks accomplished was stable and consistently over 99 percent. A simple rank order of rules based on mean number of preemptions (highest to lowest) yields the following: (1) SMPT with 1016, (2) ETOC with 942, (3) LMPT with 854, (4) FCFS with 701 and (5) MFCFS with 377. Although considered noteworthy no investigation into causes or impacts of this observation was attempted in this experiment.

The aggregate sortie effectiveness data, Tables 12 and 13, was then manipulated to obtain the basic statistics used in testing the research hypothesis; i.e., mean, variance, rank order and difference of means. Mean, variance and rank order statistics are displayed in Table 16 and difference of means is displayed in Table 21. Due to the lack of completely adequate statistical techniques for simulation models (10:3; 14:41; 17:180-181) and the common precedents established by previous researchers (2:33), the statistical data displayed in Table 16 was thus considered appropriate for purposes of this research.

Analysis of the results presented in Table 16 indicate that a difference in sortie effectiveness does exist between the five heuristics tested. There is also a difference in sortie effectiveness between the four seeds used for each test heuristic. To determine if the differences were due to chance fluctuation or were in fact significantly different (indicating they were from different populations), a statistical two-factor analysis of variance (ANOVA) was performed. The two-factor ANOVA was selected to ascertain if changing the random seed for each heuristic made a significant impact on the results obtained. Table 17 displays the performance measures obtained for each combination of heuristic and random seed and the calculated means. The two-factor ANOVA was accomplished using a level of significance of $\alpha = .05$. The resulting F statistics and F critical values are shown in Table 18. The hypothesis of no difference could not be rejected for the difference in seeds where the F statistic was 1.1599 and the F critical value was 3.490. The fluctuation of values for the performance measures are due to chance variation and are not statistically significant. This result was anticipated as changing the random seed should not have changed the scheduling philosophy within the model but should have only changed the random distribution of failures. The differences between heuristic means was significant where the F statistic was 5.69 and F critical was 3.29. It was

possible to reject the hypothesis of no difference and show the means to be from different populations.

The two-factor ANOVA was collapsed to a one-factor ANOVA for heuristics (rows). Table 19 shows the results of this analysis for a level of significance of $\alpha = .05$. It was possible to again reject the hypothesis of no difference and conclude that there was a statistically significant difference between at least one pair of means. To determine if more than one pair of means possessed this characteristic and to determine which ones, the Scheffé Method of Simultaneous Confidence Intervals (24:224) was used. Table 20 shows the calculations for each comparison of means and resultant interval. The results of these comparisons, Table 21, show that significant differences do exist between the Modified First Come First Served (MFCFS) rule as compared individually to First Come First Served (FCFS), Shortest Mean Processing Time (SMPT) and Estimated Time of Completion (ETOC). However, there is no significant difference between FCFS, SMPT, and ETOC. The Longest Mean Processing (LMPT) rule does not show any significant difference when compared to FCFS, SMPT, LMPT and ETOC.

The heuristics can be rank ordered with the combination rule ETOC producing the highest mean sortie effectiveness rate followed by SMPT, FCFS, LMPT and MFCFS respectively. The ETOC rule is a combination of the FCFS

and SMPT rules and has a variance between the two rules. The variance of the FCFS rule is second only to the MFCFS rule with respect to the highest variance. The variance of the ETOC rule was third highest and may have been influenced by the high variance produced by the FCFS philosophy used as part of the rule. The second factor in the ETOC rule was the variance of the SMPT rule. The resultant low variance of this rule is contrary to the results presented in much of the literature. Shortest process time rules have traditionally exhibited large variations in flow times. Although a direct correlation between flow times and sortie effectiveness is not drawn, it is interesting to note that the SMPT rule did have the lowest variance for this study. Boyett (2:56) experienced a similar result, stating that:

> . . . the results from the SMOPT rule were totally unexpected. As indicated earlier, much of the dissatisfaction with SPT rules or variations of SPT involved the large variance of flow times. The SMOPT rule as applied in this study is a translation of SPT to the assembly shop, however some unknown combination of relationships acted to hold flow time variance down [2:56].

The effect of the SMPT component on the ETOC rule was an offsetting factor to the relatively high variance produced by the FCFS component of the rule. The variance of the SPT rule should increase with the introduction of a preemption policy (2:52). Preemption policy is in effect in the L-COM simulation and as previously mentioned the SMPT rule ranked first, with a mean of 1016 preemptions,

the variance of sortie effectiveness, however, for this rule was the lowest of all five heuristics.

The FCFS rule consistently produced a sortie effectiveness measure higher than the MFCFS and the former was ranked in the top three rules in three of the four simulation runs (Table 16). The most consistent rule was the ETOC even with its relatively high variance of 4.15 times that of the SMPT rule.

The relative ranking of the rules and the statistical tests for significance seem to indicate that the ETOC, SMPT, and FCFS rules as a group have differences that are statistically significant when compared to the MFCFS rule. The LMPT rule is ranked between the three rule grouping and the MFCFS rule and its difference is not statistically significant in either direction. Conclusions cannot be drawn as to a best rule, but the relative ranking indicates that FCFS and SMPT rules produce better results under the given set of conditions and further that a combination rule, incorporating the best features of each of these rules, may improve performance even more.

Chapter 5

SUMMARY, CONCLUSIONS AND FUTURE RESEARCH

The objective of this research was to identify a scheduling rule or combination of rules which consistently maximizes sortie effectiveness for a TAC F-4E squadron. The simulation model used to analyze the impact of alternative heuristics in a dynamic environment was the validated Logistics Composite Model (L-COM). This model realistically simulated the operation and maintenance of an eighteen-aircraft TAC F-4E squadron encompassing the generation of approximately 160,000 tasks during an eighty-day period. Task accomplishment occurred in a complex, dynamic job shop environment where constrained resources necessitated the use of a specified scheduling philosophy. The modification of this philosophy was the focal point of the test heuristics. By changing the scheduling rules in consonance with various (available) task attributes it was possible to influence the chosen performance criterion of sortie effectiveness.

Five heuristics were formulated, inserted into the model, and allowed to operate during each eighty-day simulation run against four different random number sequences. A total of twenty simulation runs were accomplished

representing the accomplishment of 3,195,968 tasks, the generation of 31,078 sorties, and the completion of approximately four and one-half years of operations and maintenance activities.

An *a priori* hypothesis stated that there is a difference in the impact on scheduling effectiveness between alternative selected heuristics. Accordingly, five heuristics were developed consisting of Modified First Come First Served (MFCFS), First Come First Served (FCFS), Shortest Mean Processing Time (SMPT), Longest Mean Processing Time (LMPT) and a combination rule, Estimated Time of Completion (ETOC). Results of this study as supported by traditional statistical techniques (two-factor ANOVA--collapsed one-factor ANOVA--Sheffé's Simultaneous Confidence Interval comparisons) indicate that a statistically significant difference does exist between the MFCFS heuristic and the group of heuristics ETOC, SMPT and FCFS. The results of the simulations allow acceptance of this hypothesis.

The ETOC heuristic, although not statistically different than FCFS, SMPT and LMPT, did rank number one of the five rules tested. The SMPT and FCFS heuristics ranked two and three respectively with the SMPT rule exhibiting an unexpected low variance. The variance of the FCFS heuristic was relatively high, second only to the MFCFS

heuristic, and tended to increase the variance of the combination ETOC rule.

Although the objective of this study was to ascertain if alternative heuristics did impact scheduling effectiveness and subsequently the selected performance measure, sortie effectiveness, an underlying purpose was to determine if a selected heuristic or combination of heuristics could be found which would consistently maximize scheduling effectiveness in an environment such as a TAC F-4E squadron. This study has not isolated that rule but it has pointed out that changing heuristics can influence performance.

Conclusions

Selected alternative heuristics do impact scheduling effectiveness and subsequently the performance measure, sortie effectiveness, within the specific parameters of this simulation. No best rule or combination of rules has been proven to exist for all conditions within the simulation. Although the relative heuristic ranking may add to the knowledge in this field, no attempt was made to generalize the results of this study to other populations.

Future Research

Other than the usual impact of computer usage constraints associated with simulation experiments, the potential for additional research with L-COM (SIMSCRIPT I.5

or the forthcoming highly improved 2.5) in the area of scheduling appears to be practically unlimited. Many additional heuristics and combinations of heuristics could be tested to aid in completing a comprehensive treatment of the many well-known scheduling rules. In addition, other performance criterion like manpower utilization, cost, and mission effectiveness could be examined with the goal of identifying best rules for various objectives.

Similarly heuristics determined to be best performers under selected objectives could be held constant while various levels of manpower and parts constraints were examined in light of those objectives; e.g., what minimum level of maintenance manning could be achieved using the most effective scheduling heuristic associated with maximum sortie effectiveness.

Considering the fact that the Air Force is currently using L-COM to aid in the determination of resource requirements for both existing weapon systems and new weapon systems; the fact that the L-COM MFCFS rule was ranked last of the five heuristics tested; and the fact that the L-COM program changes used in this research have been retained, the future research cited in the previous paragraphs does appear to be highly warranted.

APPENDIX

SIMULATION DATA

TABLE 1

MANPOWER AUTHORIZATIONS (CONSTRAINTS) USED IN THE SIMULATIONS

Air Force Specialty Code	Shift Authorizations (24 One-Hour Shifts)																						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
301X0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
301X1	1	1	1	1	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3	3	3	1	1	1
301X3	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
301X4	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	2	2	2
322Q1	10	10	10	10	10	10	10	10	10	10	12	12	12	12	12	12	12	12	12	12	12	12	10	10
325X0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
325X1	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	3	3	3
402X0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0
421X2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	2	2
422X1	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4	4	4	4	4	2	2
422X2	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
423X0	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4	4	4	4	4	4	4	4	2	2
424X0	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
431C1	32	32	32	32	32	32	32	32	32	32	28	28	28	28	28	28	28	28	28	28	28	28	32	32
431C5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
431C6	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	0	0
432X0	9	9	9	9	9	9	9	9	9	9	12	12	12	12	12	12	12	12	12	12	12	9	9	9
432X5	0	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	0	0	0
462X0	40	68	68	68	68	68	68	68	68	48	48	48	48	48	48	48	48	40	40	40	40	40	40	40
531X0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
532X0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0
534X0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
536X0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
533X0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
922X0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

TABLE 2

EQUIPMENT AUTHORIZATIONS (CONSTRAINTS) USED IN THE SIMULATIONS

Resource Identification Number	Authorized Quantity
AM100	5
AAA00	99
MC120	3
AS300	99
DOCK1	99
DOCK2	99
DOCK3	99
DOCK4	99
DOCK5	99
DOCK6	99
DCK7	99
DCK8	99
DCK9	99
DCK10	99
DCK11	99
DCK12	99
QRARPT	99
FCFRPT	99
WXCNX	99
OPSCNX	99
COLMAN	99
RAMIN	99
RAMOUT	99
PFRPT	99

TABLE 3

SPARE PARTS AUTHORIZATIONS (CONSTRAINTS) USED IN THE SIMULATIONS

Resource Identification Number	Authorized Quantity	Resource Identification Number	Authorized Quantity
111AA	1	23730	2
111HM	1	2381A	2
111KC	1	2381M	2
111KH	1	2392A	5
111KJ	4	4111H	2
111KL	2	4112B	2
111KQ	4	4112M	3
111KS	3	4113A	2
111KT	5	4114G	2
1132C	5	4114J	3
1231H	3	4114K	2
1233K	1	4153F	2
1236K	2	4153G	1
1325A	1	42330	1
1325D	11	42610	3
1333C	25	42630	6
1333A	1	4511B	8
1334B	4	4511A	2
1334C	2	4511K	8
1342E	3	4513A	1
1343B	2	45130	3
1344A	1	4521A	2
1344C	4	4623A	2
1344K	6	4623B	1
1344L	7	4642D	2
1344M	8	4644C	4
1352A	3	471AA	4
1411A	3	4721C	7
1411F	2	47210	3
1422B	2	511AA	2
1425B	1	511AB	4
14310	1	511AD	2
1431B	2	511AE	3
1431J	7	511AF	3
1432F	4	511AG	6
1442C	2	511AJ	2
1442D	2	512AA	5
1455C	2	512CL	2
1455E	2	512CM	2
14610	1	513B0	4
2371A	1	513E0	3

TABLE 3--Continued

Resource Identification Number	Authorized Quantity	Resource Identification Number	Authorized Quantity
513H0	4	731M0	2
513HB	5	731N0	5
5211A	2	73510	3
522B0	1	73520	2
522E0	1	73530	1
52240	6	74BA0	2
52270	8	74BB0	2
71B20	8	74BC0	1
71B2A	4	74BCA	1
71B2E	3	74BCC	1
71H10	2	74BD0	1
71H20	1	74BDD	1
71H2A	3	74BE0	3
71H2Q	3	74BF0	3
71H2U	4	74BG0	1
71H3L	3	74BH0	4
71H3U	3	74BJ0	2
71H4A	2	74BK0	1
71H4L	3	74BL0	2
71H4R	3	74BM0	2
71H50	1	74BN0	1
71H5A	2	74BP0	1
71H60	2	74BPB	3
71LB0	2	74BPH	2
71LC0	1	74BQ0	1
71LD0	1	74BQA	1
71LE0	1	74BR0	2
71LJ0	4	74BS0	1
71L0A	3	74BT0	1
71MA0	3	74BU0	1
71ME0	2	74BUB	1
71MH0	2	74BUC	1
71NA0	3	74BUF	1
723A0	1	74BUL	1
723B0	2	74BUM	1
731B0	2	74BUN	2
731C0	2	64BUR	1
731D0	1	74BUS	1
731E0	2	74BV0	1
730ED	2	74BVE	3
731F0	3	74BVG	3
731G0	5	74BVR	4
731H0	5	74BVS	1
731J0	5	74370	1
731L0	4	74810	1

TABLE 3--Continued

Resource Identification Number	Authorized Quantity	Resource Identification Number	Authorized Quantity
74820	1	77J10	2
78440	3	77J2A	1
75B10	1	77J2B	1
75B40	1	9612B	1

TABLE 4

HEURISTICS

Acronym	Priority Definition	Description
MFCFS	Minimum PRI	Task with first come first served within a priority group
FCFS	Minimum T	Task with earliest arrival time at operation awaiting work set
SMPT	Minimum $\bar{P}$	Task with the shortest mean process time
LMPT	Minimum $\frac{1}{\bar{P}}$	Task with the longest mean process time
ETOC	Minimum $(T + \bar{P})$	Task with a combination of shortest mean processing time and earliest arrival time

TABLE 5

SYMBOLS USED IN HEURISTIC DEFINITIONS

Symbol	SIMSCRIPT I.5 Variable	Description
$\bar{P}$	DEL	Estimated mean process time for each task. Determined by random number generation from a probability distribution.
T	TIME	Clock time of simulation since start at zero. A system attribute of SIMSCRIPT I.5.
PRI	TPRI(KTID)	Priority determined by upper limit of group priority set. Initially established by network task priority and bounded by limits determined by user. Default modes are 10 for group 1, 20 for group 2, and 30 for group 3.
--	FLOAT	SIMSCRIPT I.5 system parameter used to convert an integer variable to a real (floating point) variable.
--	10^4	Factor used to weight the priority attribute being tested in the heuristic; i.e., $.04 * 10^4 = 400$.

TABLE 6

HEURISTIC CODING USED IN L-COM

Heuristic	Coding	Location
MFCFS	Let PRI (JBEND) = TPRI(KTID)	ALTER 998
FCFS	Let PRI (JBEND) = TIME	ALTER 998
SMPT	Let PRI (JBEND) = 10000. * DEL + FLOAT(TPRI(KTID))	ALTER 998
LMPT	Let PRI (JBEND) = 10000. * (1./DEL) + FLOAT (TPRI(KTID))	ALTER 998
ETOC	Let PRI (JBEND) = 10000. * (TIME + DEL) + FLOAT (TPRI(KTID))	ALTER 998
	<u>Other Changes</u>	
	+ N JBEND 8 4	ALTER 20
	+ N MSN 8 1 N PRI 73 SF	ALTER 36
	+ T UREC 4	ALTER 93
	+ T UVALU 3 SF	ALTER 97
	195 IF (MSN) NE (0), LET PRI (JBEND) = PRI (JBEND) - 10 + MSNPR (MSN)	ALTER 1010
	25C Let Y = IPR	ALTER 3181
	Let X = -IPT	ALTER 4557

TABLE 7

SUMMARY OF SIMULATION RUN DATA--
SORTIE EFFECTIVENESS DATA PER TEN-DAY SIMULATION PERIOD
(MFCFS)

Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness	Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness
		Seed 13				Seed 15	
0 - 10	205	186	90.75	0 - 10	205	181	88.28
10 - 20	218	199	91.28	10 - 20	218	204	93.56
20 - 30	221	189	85.50	20 - 30	221	188	85.06
30 - 40	209	192	91.84	30 - 40	209	176	84.19
40 - 50	218	201	92.19	40 - 50	218	205	94.03
50 - 60	221	198	89.56	50 - 60	221	180	81.44
60 - 70	209	191	91.37	60 - 70	209	192	91.84
70 - 80	218	200	91.72	70 - 80	218	201	92.19
		Seed 85				Seed 93	
0 - 10	205	182	88.75	0 - 10	205	182	88.75
10 - 20	218	201	92.19	10 - 20	218	205	94.03
20 - 30	221	187	84.59	20 - 30	221	187	84.59
30 - 40	209	172	82.28	30 - 40	209	187	89.47
40 - 50	218	197	90.34	40 - 50	218	190	87.12
50 - 60	221	181	81.87	50 - 60	221	179	80.97
60 - 70	209	195	93.28	60 - 70	209	189	90.41
70 - 80	218	201	92.19	70 - 80	218	192	88.06

TABLE 8

SUMMARY OF SIMULATION RUN DATA--
SORTIE EFFECTIVENESS DATA PER TEN-DAY SIMULATION PERIOD
(FCFS)

Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness	Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness
		Seed 13				Seed 15	
0 - 10	205	182	88.75	0 - 10	205	183	89.25
10 - 20	218	187	85.75	10 - 20	218	200	91.72
20 - 30	221	184	83.25	20 - 30	221	197	86.49
30 - 40	209	198	94.72	30 - 40	209	187	89.47
40 - 50	218	203	93.09	40 - 50	218	194	91.28
50 - 60	221	199	90.03	50 - 60	221	194	87.78
60 - 70	209	199	95.19	60 - 70	209	192	91.84
70 - 80	218	207	94.94	70 - 80	218	198	90.81
		Seed 85				Seed 93	
0 - 10	205	189	92.19	0 - 10	205	181	88.28
10 - 20	218	203	93.09	10 - 20	218	197	90.34
20 - 30	221	183	82.78	20 - 30	221	197	89.12
30 - 40	209	177	84.69	30 - 40	209	195	93.28
40 - 50	218	200	91.72	40 - 50	218	201	92.19
50 - 60	221	194	87.78	50 - 60	221	191	86.41
60 - 70	209	188	89.94	60 - 70	209	192	91.84
70 - 80	218	210	96.31	70 - 80	218	206	94.47

TABLE 9

SUMMARY OF SIMULATION RUN DATA--
SORTIE EFFECTIVENESS DATA PER TEN-DAY SIMULATION PERIOD
(SMPT)

Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness	Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness
		Seed 13				Seed 15	
0 - 10	205	188	91.69	0 - 10	205	187	91.22
10 - 20	218	208	95.41	10 - 20	218	204	93.56
20 - 30	221	202	91.37	20 - 30	221	195	88.22
30 - 40	209	197	94.25	30 - 40	209	201	96.16
40 - 50	218	200	91.72	40 - 50	218	201	92.19
50 - 60	221	188	85.06	50 - 60	221	192	86.87
60 - 70	209	191	91.37	60 - 70	209	195	93.28
70 - 80	218	197	90.34	70 - 80	218	199	91.28
		Seed 85				Seed 93	
0 - 10	205	182	88.75	0 - 10	205	185	90.22
10 - 20	218	192	88.06	10 - 20	218	203	93.09
20 - 30	221	187	84.59	20 - 30	221	197	89.12
30 - 40	209	194	92.18	30 - 40	209	194	92.81
40 - 50	218	203	93.09	40 - 50	218	208	95.41
50 - 60	221	192	86.87	50 - 60	221	198	89.56
60 - 70	209	199	95.19	60 - 70	209	196	93.75
70 - 80	218	203	93.09	70 - 80	218	197	90.34

TABLE 10

SUMMARY OF SIMULATION RUN DATA--
SORTIE EFFECTIVENESS DATA PER TEN-DAY SIMULATION PERIOD
(LMPT)

Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness	Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness
		Seed 13				Seed 15	
0 - 10	205	184	89.75	0 - 10	205	181	88.28
10 - 20	218	199	91.28	10 - 20	218	198	90.81
20 - 30	221	196	88.69	20 - 30	221	199	90.03
30 - 40	209	193	92.34	30 - 40	209	184	88.03
40 - 50	218	191	87.59	40 - 50	218	192	88.06
50 - 60	221	198	89.56	50 - 60	221	196	88.65
60 - 70	209	195	93.28	60 - 70	209	181	86.59
70 - 80	218	187	85.75	70 - 80	218	200	91.72
		Seed 85				Seed 93	
0 - 10	205	189	92.19	0 - 10	205	189	92.19
10 - 20	218	192	88.06	10 - 20	218	203	93.09
20 - 30	221	192	86.87	20 - 30	221	191	86.41
30 - 40	209	191	91.37	30 - 40	209	194	92.81
40 - 50	218	198	90.81	40 - 50	218	203	93.09
50 - 60	221	195	88.22	50 - 60	221	191	86.41
60 - 70	209	195	93.28	60 - 70	209	197	94.25
70 - 80	218	196	89.91	70 - 80	218	199	91.28

TABLE 11

SUMMARY OF SIMULATION RUN DATA--
SORTIE EFFECTIVENESS DATA FOR TEN-DAY SIMULATION PERIOD
(ETOC)

Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness	Period	Sorties Requested	Sorties Accomplished	Sortie Effectiveness
		Seed 13				Seed 15	
0 - 10	205	189	92.19	0 - 10	205	186	90.72
10 - 20	218	202	92.66	10 - 20	218	203	93.09
20 - 30	221	201	90.94	20 - 30	221	197	89.12
30 - 40	209	198	95.19	30 - 40	209	188	89.94
40 - 50	218	204	93.56	40 - 50	218	202	92.66
50 - 60	221	189	85.50	50 - 60	221	201	90.94
60 - 70	209	199	95.19	60 - 70	209	198	94.72
70 - 80	218	207	94.94	70 - 80	218	201	92.19
		Seed 85				Seed 93	
0 - 10	205	197	94.12	0 - 10	205	189	92.19
10 - 20	218	201	92.19	10 - 20	218	182	83.47
20 - 30	221	193	89.31	20 - 30	221	185	83.69
30 - 40	209	194	92.81	30 - 40	209	183	87.53
40 - 50	218	202	92.66	40 - 50	218	205	94.03
50 - 60	221	199	90.03	50 - 60	221	194	87.78
60 - 70	209	199	95.19	60 - 70	209	195	93.28
70 - 80	218	206	94.47	70 - 80	218	206	94.47

TABLE 12

SUMMARY OF SIMULATION RUN DATA
(AGGREGATE SORTIE EFFECTIVENESS DATA)

	0 - 80 Days		20 - 80 Days	
Heuristic	Requested	Accomplished	Requested	Accomplished
		Seed 13		
MFCFS	1719	1556	1296	1171
FCFS	1719	1559	1296	1190
SMPT	1719	1571	1296	1175
LMPT	1719	1543	1296	1160
ETOC	1719	1590	1296	1190
		Seed 15		
MFCFS	1719	1527	1296	1142
FCFS	1719	1545	1296	1162
SMPT	1719	1574	1296	1183
LMPT	1719	1531	1296	1152
ETOC	1719	1576	1296	1187

TABLE 13

SUMMARY OF SIMULATION RUN DATA
(AGGREGATE SORTIE EFFECTIVENESS DATA)

Heuristic	0 - 80 Days Requested	0 - 80 Days Accomplished	20 - 80 Days Requested	20 - 80 Days Accomplished
		Seed 85		
MFCFS	1719	1516	1296	1133
FCFS	1719	1544	1296	1152
SMPT	1719	1552	1296	1178
LMPT	1719	1548	1296	1176
ETOC	1719	1591	1296	1193
		Seed 93		
MFCFS	1719	1511	1296	1124
FCFS	1719	1560	1296	1182
SMPT	1719	1578	1296	1190
LMPT	1719	1567	1296	1175
ETOC	1719	1539	1296	1168

TABLE 14

SUMMARY OF SIMULATION RUN DATA
(TASK DATA)

Heuristic	Seed No.	Tasks Started	Tasks Completed	% Accomplished	Preemptions
MFCFS	13	161,076	160,472	99.62	428
	15	157,255	156,730	99.66	322
	85	156,540	155,947	99.62	383
	93	156,532	155,951	99.62	376
FCFS	13	160,728	159,798	99.42	685
	15	159,903	158,992	99.43	687
	85	159,697	158,781	99.43	705
	93	162,568	161,609	99.41	728

TABLE 15

SUMMARY OF SIMULATION RUN DATA
(TASK DATA)

Heuristic	Seed No.	Tasks Started	Tasks Completed	% Accomplished	Preemptions
SMPT	13	163,195	161,958	99.24	1059
	15	163,167	161,940	99.25	1048
	85	158,796	157,611	99.25	944
	93	163,403	162,164	99.24	1015
LMPT	13	160,768	159,229	99.35	811
	15	158,206	157,159	99.34	828
	35	161,111	160,004	99.31	874
	93	161,647	160,521	99.30	905
ETOC	13	165,776	164,602	99.29	951
	15	163,030	161,900	99.31	895
	85	163,310	162,187	99.31	914
	93	159,641	158,413	99.23	1008

TABLE 16

SUMMARY OF SORTIE EFFECTIVE STATISTICS

Heuristic	20-80 Days Sortie Effectiveness $\left(\frac{\text{Sorties Accomplished}}{\text{Sorties Requested}}\right)$						
	Seed 13	Seed 15	Seed 85	Seed 93	Mean	Rank Order By Mean	Variance
ETOC	92.51%	91.59%	92.05%	90.12%	91.57%	1	1.071
SMPT	90.66%	91.28%	90.89%	91.82%	91.16%	2	.258
FCFS	91.82%	89.66%	88.89%	91.20%	90.39%	3	1.828
LMPT	89.51%	88.89%	90.04%	90.66%	89.77%	4	.569
MFCFS	90.35%	88.11%	87.42%	86.73%	88.15%	5	2.462

TABLE 17

TWO-FACTOR ANALYSIS OF VARIANCE DATA

Heuristic \ Seed	i=13	15	85	93	Heuristic Mean $\bar{X}_i$
MFCFS	90.35	88.11	87.42	86.73	$88.15 = \bar{X}_1$
FCFS	91.82	89.16	88.89	91.20	$90.39 = \bar{X}_2$
SMPT	90.66	91.28	90.89	91.82	$91.16 = \bar{X}_3$
LMPT	89.51	88.89	90.04	90.66	$89.775 = \bar{X}_4$
ETOC	92.51	91.59	92.05	90.12	$91.57 = \bar{X}_5$
					$90.21 = \bar{\bar{X}}_i$
Seed Mean $\bar{X}_j$	90.97	89.81	89.86	90.11	$90.19 = \bar{\bar{X}}_j$

TABLE 18

TWO-FACTOR ANALYSIS OF VARIANCE (ANOVA) TABLE

$H_0: \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$

$H_1: \mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4 \neq \mu_5$

Source	Variation: Sum of Squares (SS)	Degrees of Freedom	Variance: Sum of Squares (MSS)	F Statistic	$\alpha=.05$ F Critical
Between Heuristics	SSR 28.7	r-1 4	7.175	$\frac{7.175}{1.2605}=5.69$	$F^4_{12}=3.26$
Between Seeds	SSC 4.3697	c-1 3	1.4565	$\frac{1.4565}{1.2605}=1.1555$	$F^3_{12}=3.49$
Unexplained (Residual)	SSE 15.127	(r-1)(c-1) 12	1.2605		
Total	48.197	19	9.892		

Decision Rule: If $F_s > F_c$, reject H_0.

Heuristics $F_s > F_c$ $5.69 > 3.26$ significant at $\alpha = .05$

Seeds $F_s < F_c$ $1.156 < 3.49$ not significant at $\alpha = .05$

TABLE 19

ONE-WAY ANALYSIS OF VARIANCE TABLE (AFTER COLLAPSE OF TWO-WAY ANOVA)

$$H_0: \mu_1 = \mu_2 = \mu_3 = \mu_4 = \mu_5$$

$$H_1: \mu_1 \neq \mu_2 \neq \mu_3 \neq \mu_4 \neq \mu_5$$

Source	Sum of Squares (SS)	Degrees of Freedom	Variance Sum of Squares (MSS)	F Statistic	α=.05 F Critical
Between Heuristics	SSR 28.7	(r-1) 4	$\frac{28.7}{4} = 7.175$	$\frac{7.175}{.8476} =$	F^4_{23}
Unexplained Residual	SSE = 15.127 + 4.3697 19.397	(r-1)(c-1) +(c-1) (5)(4)+3 23	$\frac{19.497}{23} = .8476$	= 8.47	2.80
Total	48.47	27			

Decision Rule: If $F_s > F_c$, reject H_0.

Heuristic: $F_s > F_c$ 8.47 > 2.80 significant at $\alpha = .05$

TABLE 20

CALCULATION OF DIFFERENCE OF MEANS FOR SCHEFFÉ'S SIMULTANEOUS CONFIDENCE INTERVALS

$$(\mu_1-\mu_2 = (\bar{X}_1-\bar{X}_2) \pm \sqrt{F_{.05}}\, S_p \sqrt{\frac{(n-1)}{n} c_i^2})$$

$\mu_1-\mu_2$	=	$(\bar{X}_1-\bar{X}_2) \pm 2.21705$	=	-2.24	$\pm$ 2.21705
$\mu_1-\mu_3$	=	$(\bar{X}_1-\bar{X}_3) \pm 2.21705$	=	-3.01	$\pm$ 2.21705
$\mu_1-\mu_4$	=	$(\bar{X}_1-\bar{X}_4) \pm 2.21705$	=	-1.625	$\pm$ 2.21705
$\mu_1-\mu_5$	=	$(\bar{X}_1-\bar{X}_5) \pm 2.21705$	=	-3.42	$\pm$ 2.21705
$\mu_2-\mu_3$	=	$(\bar{X}_2-\bar{X}_3) \pm 2.21705$	=	- .77	$\pm$ 2.21705
$\mu_2-\mu_4$	=	$(\bar{X}_2-\bar{X}_4) \pm 2.21705$	=	.615	$\pm$ 2.21705
$\mu_2-\mu_5$	=	$(\bar{X}_2-\bar{X}_5) \pm 2.21705$	=	-1.18	$\pm$ 2.21705
$\mu_3-\mu_4$	=	$(\bar{X}_3-\bar{X}_4) \pm 2.21705$	=	1.385	$\pm$ 2.21705
$\mu_3-\mu_5$	=	$(\bar{X}_3-\bar{X}_5) \pm 2.21705$	=	- .41	$\pm$ 2.21705
$\mu_4-\mu_5$	=	$(\bar{X}_4-\bar{X}_5) \pm 2.21705$	=	-1.795	$\pm$ 2.21705

Note:

$\bar{X}_1$ = sample mean of MFCFS.

$\bar{X}_2$ = sample mean of FCFS.

$\bar{X}_3$ = sample mean of SMPT.

$\bar{X}_4$ = sample mean of LMPT.

$\bar{X}_5$ = sample mean of ETOC.

TABLE 21

DIFFERENCE IN MEANS

	$\bar{X}_1$	$\bar{X}_2$	$\bar{X}_3$	$\bar{X}_4$	$\bar{X}_5$
$\bar{X}_1$	0	-2.24*	-3.01*	-1.625	-3.42*
$\bar{X}_2$	+2.24*	0	- .77	+ .615	-1.18
$\bar{X}_3$	+3.01	+ .77	0	+1.385	- .41
$\bar{X}_4$	+1.625	- .615	-1.385	0	-1.795
$\bar{X}_5$	+3.42*	+1.18	+ .41	+1.795	0

* Indicates significant difference at $\alpha = .05$. (It was also observed that no change in these rules occurred at the .10 level of significance).

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